NONUNIFORM POWER GENERATION IN POLYCRYSTALLINE THIN FILM PHOTOVOLTAICS

V. G. Karpov, R. Harju and G. Dorer

First Solar, LLC, 12900 Eckel Junction Rd., Perrysburg, OH 43551

ABSTRACT

We consider effects of nonuniformities on thin film photovoltaics where microscopic parameters vary between different local regions. Our experimental data on polycrystalline CdTe/CdS PV cell reveal nonuniformities of different space scales. A related theoretical problem of macroscopic parameters in randomly nonuniform thin film PV cell is solved in the effective medium approximation. The effective open circuit voltage and correlation length in the are calculated. The theory predicts hot spots caused by local currents circulating in the system under open circuit conditions.

EXPERIMENTAL

While thin films are promising candidates for PV applications [1], effects of polycrystallinity on their parameters are not well understood. Here we concentrate on one such effect: variations in parameters between different microscopic regions in the film.

There are several experimental observations pointing at nonuniformities in polycrystalline PV thin film devices.

(i) Shown in Fig. 1 is the electron beam induced current (EBIC) measured at five spots 200μm apart along a straight line in a CdTe/CdS polycrystalline cell. Since EBIC is proportional to the carrier collection efficiency, we conclude that the latter fluctuates between different spots in the device.

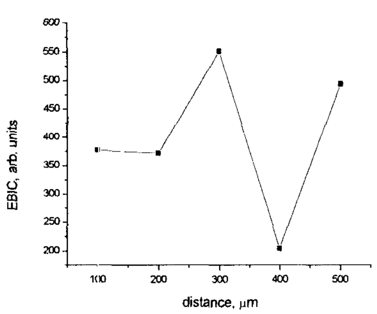

Fig. 1. EBIC variations in a CdTe/CdS PV cell; electron beam scan area 530 μm^2, energy 20kV, and current 1nA.

(ii) Laser scans from thin-film polycrystalline modules (optical beam induced currents, OBIC) show the same effect. OBIC spatial variations are maximum at forward bias near open circuit regime [2] and depend on material treatments [3].

(iii) The temperature field in an illuminated open-circuit cell is nonuniform. To visualize this effect we used thermal paper at the back wall of a CdTe/CdS cell whose front wall was illuminated (Fig. 2). We found rare (of the order of one per 100cm^2) hot spots of ~1mm size that were not associated with pinholes or other SEM visible defects.

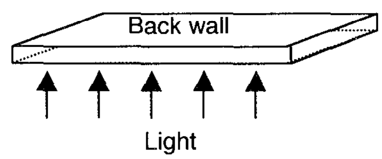

Fig. 2. Experimental setup for observations of hot spots and electric potential nonuniformities.

(iv) The electric potential V_{oc} in open circuit cells is nonuniform. Direct measurements were made at 81 spots 1cm apart in the back wall of CdTe/CdS cell whose front wall was illuminated. A thin (100Å) chrome film was deposited on the back wall. Because of its high sheet resistance (ρ~170Ω/□), local regions in the cell were effectively screened of each other. The characteristic screening length $(kT/e\rho j)^{1/2}$ [see Eq. (6) below] depends on the light intensity via the electric current density j and is estimated as 1cm for low light (~0.01 sun), and 1mm for high light (1sun) conditions. The distributions in Fig. 3 correspond to a sample that received intentionally poor back contact treatment (we were able to significantly improve uniformity by optimizing the back contact).

Regardless of what is the cause of the above nonuniformities, one has to admit that their amplitude is surprisingly large for macroscopically homogeneous film. This observation is consistent with the general understanding of the grain boundary effects in polycrystalline materials. Namely, relatively small variations in potential barriers, corresponding to the grain boundaries, have exponentially strong impact on the

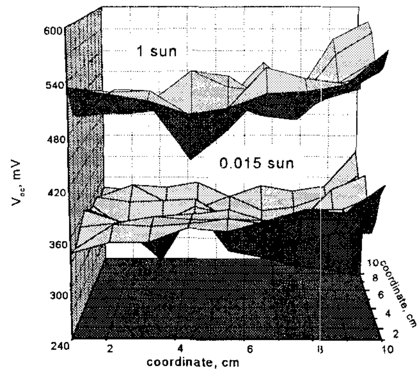

Fig. 3. Open circuit electric potential variations in the back wall plane of CdTe/CdS cell.

parameters dominated by electron activation or tunneling. This may lead to profound spatial variations in electric characteristics observed in the above experiments. In particular, we will show that the observed hot spots can be related to the nonuniformities in EBIC, and no macroscopic defects (shunts, foreign particle inclusions) are needed to explain their origin.

MODEL

To take into account variations in local properties we treat polycrystalline PV film as a system of random micro-diodes in parallel (Fig. 4). Each diode has a diameter l. An important feature of the model is that one of its electrodes

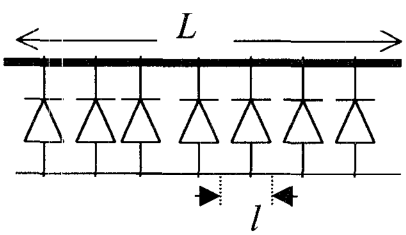

Fig. 4. System of random micro-diodes with a resistive electrode.

mimics the TCO and has a finite sheet resistance. The micro-diodes generate the current

$$j = j_0\left\{\exp\left[\frac{e(\varphi - v)}{kT}\right] - 1\right\} \qquad (1)$$

per area, where φ is the electric potential, v is the local open circuit voltage, e is the electron charge, T is the temperature and k is the Boltzmann's constant. In our model v is a random quantity varying between different points in the film (Fig. 5) and is characterized by its probability distribution g(v) (Fig. 6). The latter assumption is consistent with the measured electric potential fluctuations (Fig. 3).

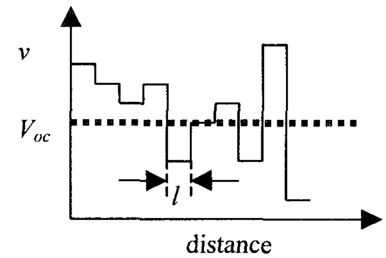

Fig. 5. Spatial variations in micro-diode open circuit voltage v and the effective macroscopic open circuit voltage V_{oc}.

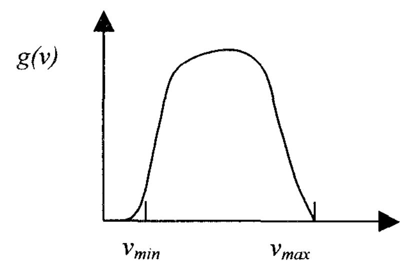

Fig. 5. Probability distribution of individual micro-diode open circuit voltages.

Because the micro-diodes in Fig. 3 are not equivalent, there are electric currents circulating in the system. This makes the measured open circuit voltage V_{oc} *different from the simple average over the local v's.* We will calculate V_{oc} and estimate the Joule heat liberated in the weak diodes due to the local currents circulating in the system under open circuit conditions.

EFFECTIVE MEDIUM APPROXIMATION

To solve the above problem we develop the effective medium approximation (also referred to as the self-consistent approximation or the mean field approximation in the physics of disordered systems and phase transitions). The effective medium sought is an imaginary homogeneous system that effectively represents the non-homogeneous system under consideration.

To determine the effective medium parameters we start with a single foreign diode embedded *into a uniform effective medium consisting of identical* diodes of an open-circuit voltage V_{oc} each. The voltage drop V across the foreign diode is a function of its bare open-circuit voltage v and V_{oc},

$$V = f(v, V_{oc}). \qquad (2)$$

This function is specified in what follows.

Given the latter function, we consider an arbitrary random diode in the original non-uniform system and approximate its surroundings by the uniform effective medium. This approximation and corresponding Eq. (2) must be valid for any of the random diodes. The self-consistency dictates that, as averaged over all such diodes, the voltage V in Eq. (2) is equal to the effective-medium open circuit voltage,

$$V_{oc} = \int dv g(v) f(v, V_{oc}). \qquad (3)$$

The effective medium parameter V_{oc} is found as a solution to the latter equation. In other words, instead of averaging insulated micro-diode open-circuit voltages, the effective medium theory self-consistently averages the voltages of micro-diodes interacting with the effective medium.

To implement the above approach one need to specify the probability distribution in Eq. (3) and the function f in Eq. (2). We used the simplest (uniform) probability distribution,

$$g(v) = (v_{\max} - v_{\min})^{-1}. \qquad (4)$$

Solving the problem of one foreign diode embedded into homogeneous array gives

$$f \approx \begin{cases} V_{oc} \text{ for } v > V_{oc} - \dfrac{2kT}{e}\ln\left(\dfrac{L}{l}\right) \\ v + 2\dfrac{kT}{e}\ln\left(\dfrac{L}{l}\right) \text{ otherwise.} \end{cases}, \qquad (5)$$

Here L is the characteristic correlation length, over which the presence of a foreign diode affects the electric potential distribution in the system. L is described by the equation

$$L = \sqrt{\frac{2kT}{j_0 \rho e}\ln\left(\frac{L}{l}\right)} \qquad (6)$$

Eq. (5) was derived assuming relative fluctuations in individual diode currents j_0 to be small as compared to $(L/l)^2$.

Note that, in spite of its cumbersome form, Eq. (5) has a simple physical mining. A large-v micro-diode ($v>V_{oc}$) generates effective forward bias applied to the surrounding medium. This causes strong forward currents screening the perturbation over a small distance and exponentially suppressing its amplitude, hence $f \approx V_{oc}$. To the contrary, a small-v micro-diode ($v<V_{oc}$) finds itself under forward bias. The voltage across it increases by δV, so that to accommodate the reverse currents generated by $(L/l)^2$ stronger diodes in the correlated are of the radius $L>>l$,

$$\exp\left(\frac{e\delta V}{kT}\right) = \left(\frac{L}{l}\right)^2.$$

Eq. (6) states that the voltage balances the latter increase drop due to the sheet resistance, that is

$$\delta V = \rho j_0 L^2.$$

Here j_0 is understood as the average over individual micro-diode currents. The latter two equations constitute a simplified derivation of Eqs. (5) and (6).

Substituting (4) and (5) into Eq. (3) yields

$$V_{oc} = \min\left\{ v_{\min} + 2\frac{kT}{e}\ln\left(\frac{L}{l}\right), v_{\max} \right\}. \qquad (7)$$

From our EBIC measurements we can estimate the characteristic nonuniformity scale l~0.2mm. Then using the parameters of our samples we get from Eq. (4) the screening length L ~4mm.

Equations (6) and (7) establish the correlation length and the effective open circuit voltage in a nonuniform PV film. However, it should be remembered that the above results are restricted to the effective medium approximation and thus catch only average variations in the local system parameters. This shortcoming is intrinsic to the effective medium approach and is well known in its other applications. The approach is generally considered a simple approximation catching general trends in the system behavior.

NONUNIFORM POWER GENERATION

Consider a weak diode, whose open circuit voltage v falls into the domain kT/e above v_{min}. In accordance with Eq. (5), there is a forward bias (2kT/e)ln(L/l) across that diode. As is seen from Eq. (1), it forces the current $J=j_0L^2$. In a sense, a weak diode acts as a shunt for the correlated area L^2, being a sink for the entire area current. Note, however, that, as opposed to the real (metal) shunt, the weak diode would not shunt the reverse bias.

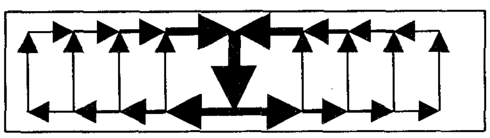

Fig. 6. Closed electric currents circulating in the system. The downward arrow represents a weak diode.

If we consider other weak diodes with v in the range (v_{min}, V_{oc}), we can divide that range in a set of domains of the width kT/e each. The diodes belonging to different domains bear exponentially different currents. Therefore, the one having v closest to v_{min} is exponentially more efficient current conductor and dominates the current distribution in the open circuit system. Its presence results in the closed currents circulating in the system as illustrated in Fig. 6. These currents cannot be collected and thus are detrimental to the photovoltaic efficiency.

One phenomenon associated with weak diodes is hot spots. Because the current generated in the area L^2 is forced through much smaller weak diode area $l^2 << L^2$, there is a high local heat density, corresponding to the power $P=j_0L^2V_{oc}$. Thermal conductivity diffuses this power over the system and thus determines the hot spot characteristic radius. We performed the standard thermal analysis of the temperature distribution caused by a cylindrical heat source (Fig. 7) across the film in contact with the glassy substrate. Far from the source thermal diffusion occurs through the glass substrate. The local temperature increase δT and the hot spot characteristic radius λ were found to be

$$\delta T = \frac{V_{oc} j_0 L^2}{2h\kappa} \text{ and } \lambda = \sqrt{\frac{\kappa}{K} Hh}\,. \quad (8)$$

Here κ and K are the film and substrate thermal conductivities respectively; the geometrical dimensions are shown in Fig. 7. Using our sample parameters gives $\delta T \sim 10°C$ and $\lambda \sim 1$mm.

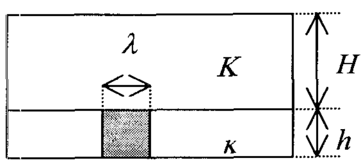

Fig. 7. Cylindrical heat source (shadowed) across the film in contact with glass substrate.

When the correlated area L^2 contains many identical weak diodes, they both shunt the currents generated in the area. Since the heat is liberated in many diodes, it is less localized and causes less temperature increase, as compared to the case of a single weak diode. Hence, the hottest spots in the system correspond to configurations where there is only one weakest diode in the correlated area. The concentration of such spots can be estimated from the Poisson's distribution,

$$N = \frac{1}{L^2} \exp\left(-\frac{L^2}{l^2} \frac{eT}{v_{max} - v_{min}} \right) \quad (9)$$

We applied this result to the hot spots observed in our samples. By putting L/l=20 and $N \sim 0.01 cm^{-2}$, we estimated from Eq. (9) v_{max}-v_{min}=0.6eV, which is qualitatively consistent with our direct measurements of electric voltage distribution in Fig. 3.

CONCLUSIONS

In conclusion, we presented data on polycrystalline cell nonuniformities in EBIC, electric potential distributions and temperature. A related theoretical problem of macroscopic parameters in randomly nonuniform thin film photovoltaics is solved in the effective medium approximation: the effective open circuit voltage and the correlation length are calculated. The theory predicts hot spots caused by local currents circulating in the system under open circuit conditions. This prediction is consistent with our observations.

This work was supported in part by NREL Thin-Film Partnership contract ZAK-817619-17.

REFERENCES

[1] R. H. Bube, *Photovoltaic Materials*, Imperial College Press, 1998.
[2] I. L. Eisgruber, R. J. Matson, J. R. Sites, K. A. Emry, *Proceedings of the First World Conference on Photovoltaics*, Waikola, Hawaii, 1994, 283-286.
[3] S. A. Galloway, A. W. Brinkman, K. Durose, R. P. Wilshaw, and A. J. Holland, *Appl. Phys. Lett.*, 68, 3725 (1996).